

Systems Integration Processes for NASA Ares I Crew Launch Vehicle

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Abstract

NASA's Exploration Initiative will require development of many new elements to constitute a robust system of systems. New launch vehicles are needed to place cargo and crew in stable Low Earth Orbit (LEO). This paper examines the systems integration processes NASA is utilizing to ensure integration and control of propulsion and non-propulsion elements within NASA's Crew Launch Vehicle (CLV), now known as the Ares I. The objective of the Ares I is to provide the transportation capabilities to meet the Constellation Program requirements for delivering a Crew Exploration Vehicle (CEV) or other payload to LEO in support of the lunar and Mars missions. The Ares I must successfully provide this capability within cost and schedule, and with an acceptable risk approach. This paper will describe the systems engineering management processes that will be applied to assure Ares I Project success through complete and efficient technical integration. Discussion of technical review and management processes for requirements development and verification, integrated design and analysis, integrated simulation and testing, and the integration of reliability, maintainability and supportability (RMS) into the design will also be included.

The Ares I Project is logically divided into elements by the major hardware groupings, and associated management, system engineering, and integration functions. The processes to be described herein are designed to integrate within these Ares I elements and among the other Constellation projects. Also discussed is launch vehicle stack integration (Ares I to CEV, and Ground and Flight Operations integration) throughout the life cycle, including integrated vehicle performance through orbital insertion, recovery of the first stage, and reentry of the upper stage. The processes for decomposing requirements to the elements and ensuring that requirements have been correctly validated, decomposed, and allocated, and that the verification requirements are properly defined to ensure that the system design meets requirements, will be discussed.

Introduction

President George W. Bush announced the Vision for Space Exploration (VSE) in January 2004. The vision outlines a bold program for space exploration with the following components.¹

- Return the Space Shuttle safely to flight. (This objective was accomplished with the STS-114 and recent STS-121 return-to-flight missions of the Space Shuttle *Discovery*.)
- Complete the International Space Station (ISS) and retire the Space Shuttle by the year 2010.

- Develop the Crew Exploration Vehicle (CEV) no later than 2014 (with a goal of 2012) and return to the Moon no later than 2020.
- Implement a sustained and affordable robotic and human exploration program and extend human presence across the solar system.

The Exploration Systems Architecture Study (ESAS) was conducted in the summer of 2005 in order to define the Design Reference Missions (DRMs) and vehicle concepts for the CEV, launch vehicles, and other architectures necessary to accomplish the VSE. The results of the ESAS served as the Point-Of-Departure (POD) vehicle architecture and the basis of the current NASA exploration program. The ESAS architecture sought to maximize commonality between missions to the ISS, the Moon, and Mars. The architecture definition also sought to separate crew and cargo payloads to the maximum extent possible. Definitions for each vehicle included the following.

- A CEV will be designed to support a crew of 6 for missions to Mars and a crew of 4 for lunar missions. The CEV will also support missions to the ISS from its initial operational capability through 2016.
- A CLV will be designed to launch the CEV into LEO. (The CLV is now known as the Ares I launch vehicle.)
- A heavy-lift Cargo Launch Vehicle (CaLV), now known as the Ares V, will be designed to launch components needed for lunar missions into LEO. These include an Earth Departure Stage (EDS) and Lunar Surface Access Module (LSAM). The CEV is designed to dock with the EDS and LSAM in LEO prior to Trans-Lunar Injection (TLI).

Initial development focuses on the Ares I and the CEV to accomplish the mission for crew and cargo delivery to and from the ISS. A DRM for CEV transport to the ISS is shown in Figure 1.

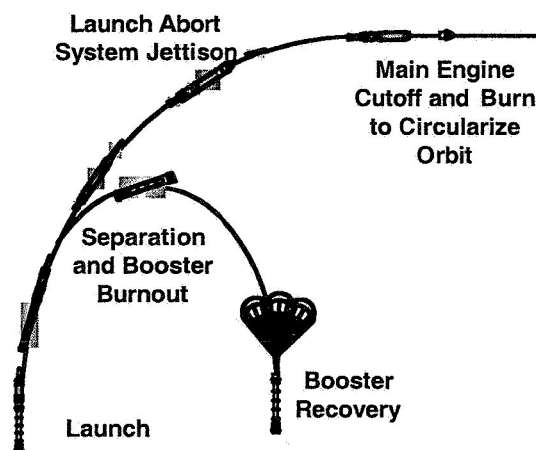


Figure 1. CLV DRM

The ESAS Final Report² outlined a recommended development approach for the components of the Ares I, which included the following:

- A first stage booster, derived from a 4-segment Space Shuttle Reusable Solid Rocket Motor (RSRM). (In subsequent trade studies, this concept was modified to a 5-segment RSRM in order to provide increased performance and commonality with the heavy-lift CaLV.)
- A new second stage, powered by a derivative of the Space Shuttle Main Engine (SSME). (Subsequent trade studies modified this design to the J-2X engine, which was used on upper stages in the Saturn V launch vehicle during the Apollo program.)

The integrated Ares I stack also includes the Crew Module, Service Module, and Launch Abort System (LAS), as shown in Figure 2.

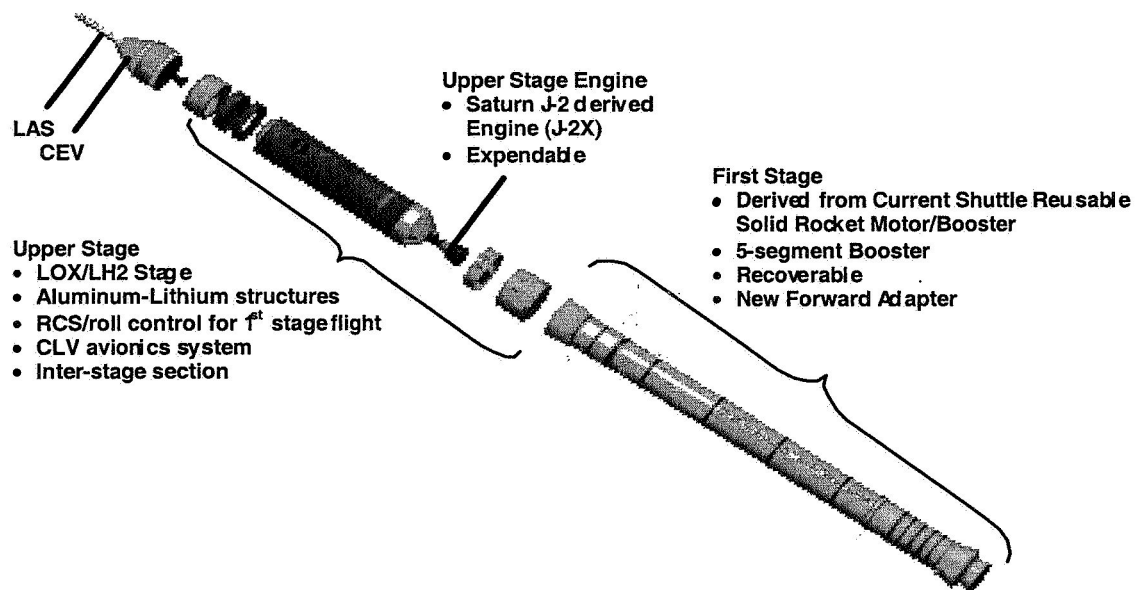


Figure 2. Schematic of the Ares I CLV

Background

In undertaking the development of Ares I, NASA has considered a number of factors in selecting an approach for vehicle management and development. Due to the lessons that have been learned from recent programs and recent studies, it has been decided that NASA will retain the role of vehicle integrator. These activities will be managed and conducted by a NASA team led by the George C. Marshall Space Flight Center (MSFC) and will be comprised of NASA and support contractor personnel from almost every NASA Center.

A number of lessons learned³ and recent Government studies into space-related program failures have pointed to a need for the Government to take a lead role in Program Management (PM), Systems Engineering and Integration (SE&I), and Mission Assurance (MA). The Defense Science Board/Air Force Scientific Advisory Board Joint

Task Force in 2003 found that the U.S. Air Force (USAF) “should develop a robust SE [Systems Engineering] capability to support program initiation and development” and should specifically,

- “Reestablish organic government systems engineering capability by selecting appropriate people from within government, hiring to acquire needed capabilities, and implementing training programs; and
- In the near term, ensure full utilization of the combined capabilities of government, Federally Funded Research and Development Center (FFRDC), and Systems Engineering and Technical Assistance (SETA) system engineering resources.”⁴

Likewise, a NASA initiated study in 2005⁵ of the Space Shuttle Program found that there were a number of big lessons to be learned about the importance of integration. Some of these key findings for future programs included;

- Develop and maintain a strong integration team throughout the program life cycle.
- Empower Integration teams to challenge project elements on issues of design flaws and the interactions among elements.
- Integration and Element engineering should be staffed with the best in their field.
- Transition to operations should be made consistent with vehicle operational capabilities embedded in the design.

Another recent Government study that analyzed failures within the U.S. space programs came to similar conclusions. This study, by the Aerospace Corporation, focused on the effects of acquisition reform efforts of the 1990s. This period saw the Department of Defense (DoD) and NASA reduce the Government role in providing technical oversight and specifications and standards. During this time frame, over \$11B in U.S. assets were lost. A National Security Space Reexamination directed the Space and Missile Command (SMC) and the National Reconnaissance Office (NRO) to reintroduce adherence to key specifications and standards and to revamp Government SE&I capabilities. This study also found some common threads among space failures, including:

- Incomplete requirements flow-down and implementation;
- Misleading requirements language;
- Insufficient verification of ad-hoc adaptation;
- Lack of independent verification;
- Unexpected interaction among subsystems, between hardware and software, or between launch vehicle and satellites;
- Over-optimistic “heritage” assumptions;
- Inability to handle software risk;
- Ineffective verification and validation; and
- Ineffective communication processes.

As a result of these various problems within the DoD, the USAF has completely redirected its space-related program management and systems engineering approaches.⁶ In 2002, the SMC was directed to begin a revitalization of its in-house SE&I capabilities. The USAF had found that “the core of effective program management is disciplined technical oversight and systems engineering.” The directive also noted a “need for being proactive in revitalizing a commitment to world-class systems engineering and program management.”

Role of Vehicle Integration

The Ares I Vehicle Integration (VI) Office is responsible for the systems integration processes NASA is utilizing to ensure integration and control of propulsion and non-propulsion elements within NASA’s Ares I Project. The objective of the Ares I is to provide the transportation capabilities to meet the Constellation Program requirements for delivering a CEV or other payload to LEO in support of the lunar and Mars missions. The Ares I must successfully provide the capability within cost and schedule with an acceptable risk approach. This paper will describe in detail the systems engineering management processes that will be applied to assure Ares I Project success through complete and efficient technical integration. Discussion of technical review and management processes for requirements development and verification, integrated design and analysis, integrated simulation and testing, and the integration of RMS into the design will also be included.

The Ares I Work Breakdown Structure (WBS) (Figure 3) is part of the overall System Structure illustrated in the Constellation Systems Engineering Management Plan (SEMP) (CxP 70013). It provides a framework for the Project hardware/software, management, engineering, and integration and will be used to:

- Identify products, processes and data,
- Organize risk management analysis and tracking,
- Enable configuration and data management,
- Organize work packages for management of engineering and Safety and Mission Assurance (S&MA) support, work orders and materials/parts ordering, and
- Organize technical reviews and audits.

The WBS will be the formal structure used to develop the system—and its interfaces—from concept through operations.

5	Constellation Systems Launch Vehicle Project
5.1	Project Management
5.1.1	Project Mgmt and Administration

5.1.2	Business Management
5.1.3	Contractor Relationships
5.1.4	Technical Reviews
5.1.5	Information Technology Mgmt
5.1.6	Adv Planning & Special Studies
5.2	Vehicle Integration
5.2.1	Systems Integration and Control
5.2.2	Systems Requirements and Verification
5.2.3	Flight Test Integration
5.2.4	Integrated Design and Analysis
5.2.5	Vehicle Integration and Operations
5.2.6	Avionics Integration and Vehicle Systems Test
5.3	S&MA
5.4	Science & Technology
5.5	Payloads
5.6	Aircraft/Spacecraft
5.7	Mission Operations System
5.8	Crew Launch Vehicle
5.8.1	First Stage
5.8.2	Upper Stage
5.8.4	Upper Stage Engine
5.8.4.1	Element Management
5.8.4.2	Government Furnished
5.8.4.3	Prime Contract
5.9	Ground System(s)
5.10	Systems Integration and Testing

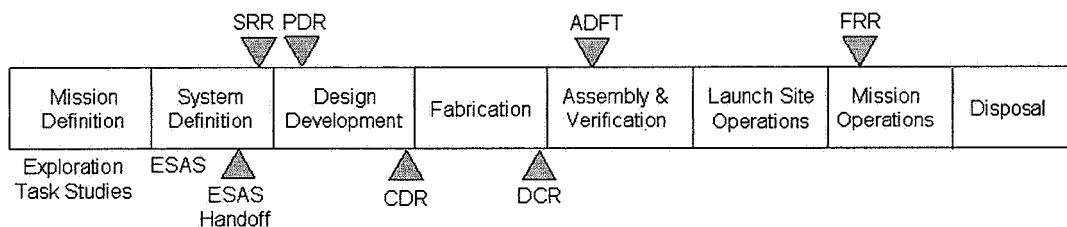
Figure 3. Ares I WBS

Technical Review Process

The NASA VI approach will be to utilize a structured technical review process throughout the design, development, and testing phases of the Ares I vehicle. Technical reviews are planned throughout the life cycle and are driven by the milestones identified below. The Ares I development phases and milestones are shown in Figure 4.

- SRR: System Requirements Review for Ares I
- PDR: Preliminary Design Review for Ares I
- CDR: Critical Design Review for Ares I
- DCR: Design Certification Review for Ares I
- ADFT-1: Ascent Development Flight Test 1
- OFT-1: Orbital Flight Test 1
- OFT-2: Orbital Flight Test 2
- ISS-1: First Flight of the Ares I to the International Space Station (ISS)

Figure 4. Ares I Development Phases and Milestones



NASA Procedural Requirement (NPR) 7123.1, NASA Systems Engineering Processes and Requirements, is the top-level document governing Technical Reviews.⁷ It should be noted that, while meeting the intent of NPR 7123.1, the life cycle strategy for Ares I has been tailored from the standard milestone set prescribed by the NPR. The Mission Concept Review (MCR) objectives have been satisfied by the ESAS. Objectives of Systems Definition Review (SDR) will be met by Ares I participation and support to the Constellation Program SDR. The Ares I will establish feasible final concepts with respect to technical performance—and the indirect parameters of cost and schedule—by the completion of the Ares I system-level PDR.

The CSLV VI team will be responsible for the planning and conduct of all CSLV technical reviews. All reviews will have a review plan and will be conducted using an automated Review Item Discrepancy (RID) tool that is identified in the Ares I Configuration and Data Management (CDM) Plan. All reviews will comply with Marshall Procedural Requirement (MPR) 8060.3, Requirements and Design Reviews, MSFC Programs and Projects, and the Ares I CDM Plan. The Pre-board will be co-chaired by the Ares I Chief Engineer (or designee) and VI representative. The Board will be co-chaired by the CSLV Project Manager and Constellation Program Representative.

Technical reviews will occur relative to the maturity of the associated technical baselines, as opposed to calendar milestones. They will be conducted in a top-down sequence from the system, to element, to subsystem, to component level, as required. Control gate reviews (PDR, CDR, DCR, Flight Readiness Review (FRR), etc.) will be conducted in a bottoms-up sequence from component, to subsystem, to element, to system-level, as required. A key entry criterion for each review will be verification that

the previous level review has been satisfactorily completed. For the SRR, entry and success criteria are detailed in the Ares I SRR Plan (CxP 70006). The SEMP will be updated and distributed prior to each milestone review to portray the current VI management processes, products, roles, and responsibilities.

SRR: System Requirements Review for Ares I

The objective of the Ares I SRR will be to determine the adequacy of the system requirements and the optimization, correlation, completeness, and risks associated with the allocated technical requirements. The SRR will demonstrate that the Constraints and Restrictions Document (CARD) requirements have been properly analyzed, functionally decomposed, allocated, and validated, and will assure that the Ares I Systems Requirements Document (SRD) is clear, achievable, responsive and appropriate to fulfill the mission needs.

PDR: Preliminary Design Review for Ares I

The overall objective of the Ares I PDR will be to demonstrate that the preliminary design meets all system-level requirements with acceptable risk. It will show that the best design option has been selected (based on documented trade studies and design analysis cycles), interfaces identified, and verification methods satisfactorily planned. It will also establish the basis for proceeding with detailed design. As a result of successful completion of the PDR, the “design-to” baseline will be approved and authorization to proceed to final design will be granted.

CDR: Critical Design Review for Ares I

The purpose of the CDR will be to exhibit the complete system design in full detail, ascertain that technical problems and design anomalies have been resolved, and ensure that the design maturity justifies the decision to initiate fabrication/manufacturing, integration, and verification of mission hardware and software. After successful completion of the CDR, the “build-to” baseline, production, and verification plans will be approved. Approved drawings will be released and authorized for fabrication. Successful completion of the CDR will also authorize coding of deliverable software (according to the “build-to” baseline and coding standards presented in the review), and system qualification testing and integration. All open issues must be resolved with closure actions and schedules.

DCR: Design Certification Review for Ares I

The purpose of the DCR will be to ensure that qualification demonstrated design compliance with functional, performance, human rating, interface, and induced environment requirements. The DCR will follow the system CDR and will occur after qualification tests and modifications to resolve qualification-related actions. The DCR will address the design requirements, make an as-designed comparison, assess what was built to meet the requirements, and review substantiation.

Ascent Development Flight Test (ADFT)-0

ADFT-0 is an early demonstration flight test of the Ares I configuration. It will be an unmanned test flight utilizing a Space Shuttle Solid Rocket Booster (SRB) First Stage and staging systems. The SRB will be a 4-segment RSRM with a simulator for the fifth segment to get vehicle shaping. The other principle vehicle elements will consist of high-fidelity simulators of Upper Stage, Upper Stage Engine, CEV, and LAS. The ADFT-0 will utilize the existing Shuttle pad and MLP systems for this flight and will minimize ground-provided services, systems, and assets. This mission will test/exercise several segments of the overall launch complex and vehicle.

ADFT-1:

ADFT-1 will be the first Ares I test flight. It will be an unmanned test flight utilizing a ARES I final design First Stage and staging systems. The other principle vehicle elements will consist of high fidelity simulators of Upper Stage, Upper Stage Engine, CEV, and LAS. Since the ADFT team will be in a facility modification/development posture for the pad and Mobile Launch Platform (MLP) systems during this period, the intent will be to minimize ground-provided services, systems, and assets. The mission will test/exercise several segments of the overall launch complex and vehicle.

Orbital Flight Test (OFT) -1 :

OFT #1 will be the second test flight of the Ares I. It will be an unmanned test flight utilizing an Ares I final-design First Stage and staging systems. Other principal vehicle elements will consist of an active proto-flight unit for Upper Stage and J-2X engine and CEV/LAS that will have full propellant load for the SM.

OFT-2:

OFT #2 will be the third test flight of the Ares I. It will be an unmanned test flight utilizing an Ares I final-design Booster Stage, Upper Stage, and Upper Stage Engine. The CEV/LAS vehicle elements will utilize a Command and Service Module (CSM) test segment that replicates the final segment design.

ISS-1: First Flight of the Ares I to the ISS with Humans, Flight Readiness Review (FRR-5)

ISS-1 will be the first flight of the Ares I to the ISS with a human crew. The purpose of the FRR for the ISS-1 flight is to examine verification results (including all previous flights) to ensure compliance with all systems and performance requirements for a safe and successful launch in the ISS-1 configuration. This FRR will occur after the Ares I has been configured for launch. As a result of successful FRR completion, technical and procedural maturity will exist for Ares I launch and flight authorization and, in some cases, initiation of Ares I operations. Principal review objectives will be to:

- Receive certification that flight operations can safely proceed with acceptable risk. (Certification of Flight Readiness (CoFR) is issued.)

- Confirm that the Ares I and supporting elements are properly configured and ready for launch.
- Establish that all interfaces are compatible and function as expected.
- Establish that the Ares I state supports a launch “go” decision based on go/no-go criteria.

VI Organization

The VI Organization is structured in accordance with the functions allocated to it by the Ares I WBS (Figure 3). WBS Managers are assigned for each of the major segments, which represent the key items of Vehicle Integration.

- Systems Integration and Control
- Systems Requirements and Verification
- Flight Test Integration
- Integrated Design and Analysis
- Vehicle Integration and Operations¹
- Avionics Integration and Vehicle Systems Test

The Systems Integration and Control WBS element is responsible for overall systems engineering planning and processes. This element will develop and maintain the processes for configuration management and control, knowledge management, systems analyses, and technical reviews. The Systems Requirements and Verification WBS element is responsible for the development of system requirements, interface requirements between major hardware elements and the verification planning for all system requirements. The Flight Test Integration element is responsible for the planning and execution of flight test in support of the Ares I system design (Note: an organizational change in spring 2006 moved this responsibility to a new organization). The Integrated Design and Analysis WBS element is responsible for systems analyses that lead to the complete analytical integration of all Ares I vehicle elements. The Vehicle Integration and Operations WBS element is responsible for the planning and design of all Ares I assembly processes, logistics planning, operations support planning, and managing the integration of RMS into the vehicle design. The Avionics Integration and Vehicle Systems Test WBS element is responsible for developing avionics and software requirements and architectures that are consistent with the integrated vehicle design. This element is also responsible for the planning and design of an integrated system testing and simulation capability that can be used to verify hardware and software functionality in an integrated and evolving environment as the Ares I design and development matures.

Integration Structure and Processes

¹ Evolution of Project Ares development has led to the VI Office recommending that this element be divided into two constituent parts, Operations & Logistics and Operability Design and Analysis. This change is still pending at the time of this writing.

Ares I horizontal and vertical integration will be achieved through the Vehicle Integration Control Board (VICB), which is chaired by the VI Manager, and staffed by the VI Chief Engineer, the VI WBS Managers, the Element SE&I Managers, and the S&MA. The VICB is supported by both staff and matrixed personnel assigned by line organizations to Integration Groups (IGs) and Technical Panels (TPs). IGs and TPs function as integration and engineering forums to promote communication and to coordinate the technical activities of the various organizations and elements. IGs will be led by the VI WBS Manager who is responsible for several related technical disciplines. The TPs will coordinate discipline specific problems and issues. IGs and TPs will have membership from the Exploration Launch Office (ELO), S&MA, the Engineering Directorate (ED), the Elements, and other projects (such as the CEV) as required. All IGs and TPs are chartered by the VICB. Specific IGs and their relationship to the current panels are shown in Figure 5.

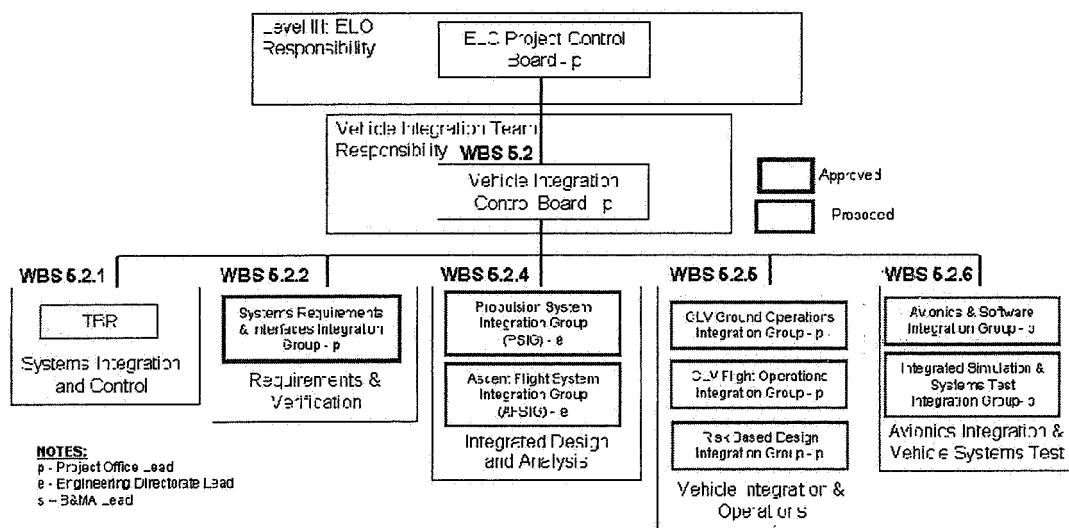


Figure 5. ARES I Project IGs and TPS

Issues affecting multiple elements and disciplines will flow down from the Ares I Project and/or Ares I VI WBS managers to the IGs and then to their TPs for assessment and proposed resolutions (issues may also originate from ED, S&MA, or within the panels and groups themselves). IGs and TPs will review and provide recommendations to the WBS managers on technical issues related to vehicle integration.

The TPs will make recommendations to the IGs, who report to VI WBS Managers. They, in turn, will make recommendations to the VICB, which will make recommendations to the Ares I Project, with Vehicle Engineering Review Board (VERB) concurrence. The VERB is chaired by the Ares I Chief Engineer, and serves as an independent engineering panel on integrated vehicle issues. Actual decisions, based on VICB recommendations, will be made by the Project, via the Project Control Board

(PCB). Issues confined to the scope of a specific element are reviewed by the Element Engineering Review Boards (ERBs) and then forwarded directly to the PCB, without going through the VICB.

Concluding Remarks

The Vision for Space Exploration that NASA is undertaking is a significant management and technical challenge. Developing a reliable, robust launch vehicle will provide a significant capability to achieve this bold vision. In order to meet these management and technical challenges, NASA has structured an oversight process that will stand the tests and challenges during the design and development of the Ares I vehicle. Clearly, lessons learned from past programs and recent failures show the need to maintain a core competency for systems engineering throughout the life cycle of a project. Through the Ares I Vehicle Integration activity, NASA has committed to developing and maintaining this capability within the Constellation Program. This should lead to a revitalization of program management and technical oversight within NASA that will enable a sustainable, affordable approach to space exploration for the decades to follow.

References

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⁵ Space Shuttle Integration Lessons Learned, Bejmuk, Boeing Corporation, 2005.

⁶ Arnold, Lt. Gen. Brian A. Department of the Air Force, Memorandum to SMC ALL. Subject: Systems Engineering. With Attachments. 06 May 2002.

⁷ NPR 7123.1, NASA Systems Engineering Processes and Requirements